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Research papers

Modelling the long-term suspended sedimentological effects on stormwater pond performance in an urban catchment

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ABSTRACT

The influence of long-term suspended sediment dynamics on stormwater pond performance should not be ignored, but is often neglected in pond design and performance evaluation. This paper provides systematic simulated quantification of long-term suspended sedimentological effects on stormwater pond performance. Integrated hydrological and two-dimensional hydro-morphodynamic modelling and simulations were carried over a 32-year period (1984–2015) covering 3896 rainfall events with a wide range of rainfall volumes, durations and intensities. Three event-based hypothetical rainfall scenarios: non-flood condition (5-year), sewer design condition (30-year), and river flood condition (100-year) rainfall events with 1-h duration, were also simulated for comparison between the traditional event-based approach and the novel approach presented in this study. Simulation results show that the flood peak attenuation and delay are more pronounced for small (< 5-year) and medium (< 30-year) flood events. The long-term continuous simulation results indicate that the pond provides positive annual trap efficiencies varying from 2% to 69% for 31 of 32 years, providing long-term water quality benefits downstream. However, an extreme rainfall event in year 2012 flush out the accumulated sedimentation as a shock load to the downstream river, leading to a negative trap efficiency of −11%. The spatially averaged sediment deposition rate, as predicted by the model, varies with a mean (SD) of 2 (1.34) cm/year over the study period, which resulted in a 24% loss in the pond's volume over 32 years. The impact of the loss in storage on pond flood attenuation capacity are explored at regular time intervals over the study period. The results indicate that reduction in the pond's flood attenuation capacity is relatively more pronounced for medium (30-year) and extreme (100-year) flood events than the frequent small flood (5-year) events. The variation in annual sediment loading with rainfall quantities and patterns are also explored.

1. Introduction

1.1. Background

In recent years, stormwater ponds (a.k.a. retention ponds, wet ponds, wet extended detention ponds) are increasingly being regarded as the promising option for stormwater management (Lawrence et al., 1996; Krishnappan and Marsalek, 2002a,b; Biggs et al., 2005) in the UK and many other countries. Stormwater ponds provide a range of benefits including flood attenuation, sediment trapping, treatment of diffuse pollution, health and wellbeing, and attract a diverse range of water birds and aquatic biota (Lawrence and Breen, 1998; Bishop et al., 2000; Persson and Pettersson, 2009; Woods Ballard et al., 2015). In stormwater quality management, sediment control is an essential, integral and dynamic part of the system (Persson and Wittgren, 2003). The catchment's characteristics and local climate play an important role in the amount and timing of sediment delivery to river systems (Ashmore and Day, 1988; Asselman et al., 2003; Lawler et al., 2003; Yang et al., 2003; Zhu et al., 2008; Bussi et al., 2016). Sedimentation provides various benefits to river ecosystems by supplying nutrients

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necessary to maintain high floodplain productivity that enables succession and transitions between habitats (Ward and Stanford, 1995; Mouw et al., 2009). However, excessive sedimentation in urban rivers may lead to a number of adverse ecological and environmental consequences as the loading of suspended sediment from an urban environment is significantly higher than that in rural catchments (Arias et al., 2013; Poleto et al., 2009). This is because increased impermeable surfaces in the urban environment shield and arrest sources of coarse material and disproportionally increase fine materials in stormwater runoff (Brodie and Dunn, 2009; Savage, 2005). Fine sediments harbour nutrients, pollutants and coliform bacteria which are generated from the urban environment and transported by storm runoff (Jartun et al., 2008). This stresses the biological, chemical and physical integrity of the receiving water through eutrophication, toxification, limited permeability and reduced oxygen delivery. Further siltation reduces the flow capacity of the river channel and functional capacity of the stormwater systems (Butler and Karunaratne, 1995) that can increase downstream flood risk. Moreover, contaminants associated with suspended sediment particles and dissolved solutes in stormwater runoff are rather more difficult to manage than those associated with coarse particles (Birch et al., 2006).

Stormwater ponds are generally regarded as an effective option for suspended sediment trapping which serve as both “nature’s supermarket” and “nature’s kidneys”. Ponds improve urban runoff quality through a series of processes including sedimentation, filtration, chemical precipitation, microorganism-degradation and plant-adsorption (Kantrowitz and Woodham, 1995; Mitsch and Gosselink, 2007; Su et al., 2009). Bioremediation, absorption and oxidation processes facilitate nutrient and heavy metal removal from the stormwater runoff (Sansalone et al., 1998; Peng et al., 2009; Woods Ballard et al., 2015). Vegetation, or varying planting density and emergence, assists in increasing the surface roughness and enhances fine sediment detention (Braskerud, 2001). Furthermore, stormwater ponds provide flood storage through interception, which minimises the downstream flood risk by attenuating and delaying the urban runoff (Ellis et al., 1995; Koskiaho, 2003; Woods Ballard et al., 2015). The flood attenuation and improvements in water quality derived from the ponds are strongly interrelated and need to be considered together to optimise their potential benefits and promote local actions (Lawrence et al.,1996; Wilkinson et al., 2014). Despite the recognised multiple benefits, there are still concerns over the long-term performance of ponds in urban catchments as the performance of the ponds varies considerably with rainfall and flow conditions.

In the UK, most of the guidelines on sustainable drainage systems have come from industry research bodies (e.g. CIRIA, Woods Ballard et al., 2015), so there is relatively limited academic work exploring the long-term hydrological performance of the ponds over their whole life cycle using numerical methods. This is partly attributed to the complex physical processes associated with the flow and sediment dynamics in the ponds and the lack of good quality (finer resolution and long-term) spatial and temporal field data sets to calibrate and validate numerical modelling techniques (Hall et al., 1993; Deletic et al., 2000; Willems, 2013). The long-term impact of sediment erosion, transport and deposition in ponds on flood attenuation capacity is significant but seldom considered in planning urban ponds (Verstraeten and Poesen, 1999). In contrast, there are adequate guidelines on hard engineering measures for which models are generally regarded as mathematically more robust and predictable. In this context, it is essential to develop numerical models and tools to evaluate the long-term performance of stormwater ponds to bridge the gap between hard engineering approaches and natural systems.

1.2. Numerical models

Numerical models which are typically adopted to evaluate the performance of stormwater ponds can be categorised as: black box, conceptual and hydrodynamic. The first two types are relatively simple, and demand modest data compared to the third; black box and conceptual models are commonly used to predict averaged net annual sediment budget of a pond. However, the empirical equations based on the Hazen surface loading theory (Krishnappan and Marsalek, 2002a,b) that is mostly used in the first two types of model may not adequately represent underlying physical processes of the systems. Furthermore, the empirical relationship derived for a specific pond system is not always reliably transferable to another due to the uniqueness of each system. Thus, the black box and conceptual models have limited usefulness in capturing the pond system’s spatial and temporal dynamics, particularly under extreme conditions. Hydrodynamic models, which are based on the deterministic solution of hydraulic equations (Bruen and Yang, 2006), can provide more insight into the physical processes that occur within the pond system.

A review of previous hydrodynamic studies demonstrates that the effect of a pond on flow and sediment dynamics is usually assessed using two or three-dimensional event-based simulations (Adamsson et al., 2003; Benelmouffok and Yu, 1989; Persson, 2000; Walker, 2001). To assess the impact of long-term sedimentation, Pender et al. (2016) adopted a one-dimensional sediment transport model using HEC-RAS to evaluate changes in the channel capacity after 50 years of sediment transport. However, these approaches inevitably have inherent limitations when fully capturing the hydrodynamics of the system are concerned. Firstly, the lifespan of stormwater ponds is typically longer than 25 years (Woods Ballard et al., 2015), whereas deriving plausible rainfall and corresponding flood events to represent the diversity in the natural rainfall and flow scenarios is often subjective in event-based simulations. This is because of the variability and intermittent nature of stormwater runoff, the runoff duration for different events with comparable peak flows can vary considerably (Cristiano et al., 2017; Fletcher et al., 2013; Gericke and Smithers, 2014). Similarly, rainfall exhibits large natural variation in amount and duration. The inherent randomness in rainfall, runoff and consequent sedimentation processes results in a wide range of event combinations with various sediment loading, durations and frequencies of occurrence of flows (van Buren et al., 1997; Werner and Kadlec, 1996). This leads to practical problems in identifying the critical storm event that could yield the highest flow or volume for event-based simulations. In addition, a considerable amount of sediment can accumulate in the retention pond over time and there is a potential for future remobilisation of constituents into the river system during larger flood events which may exacerbate flow and pollutant levels downstream (Lawrence et al., 1996). Recent field-based research using novel fine sediment tracing methodology has identified that sediment is only temporarily detained in Blue-Green features, providing evidence of cumulative rainfall-runoff impact on re-suspension and conveyance of sediment within and through established Blue-Green features (Allen et al., 2015a,b). Event-based simulations capture neither the processes of sediment accumulation in the pond nor remobilisation into the river. Secondly sediment dynamics in the pond is a three-dimensional process with eddies and recirculation (Adamsson et al., 1999); one dimensional long-term simulation may not fully capture the morphodynamic processes of the pond system.

The dominant technical uncertainty in long-term performance limits the likely adaptation of stormwater ponds in urban settings. In this regard, this study aims to provide the first systematic and detailed quantification of long-term performance of a retention pond with comprehensive consideration of flow and sediment dynamics. This study focuses on a stormwater pond in the Newcastle Great Park, in the upstream part of the Ouseburn catchment, Newcastle-upon-Tyne, North-East England. A conceptual hydrological model is used to quantify the urban runoff from the Newcastle Great Park development to the stormwater pond, and two-dimensional full hydro-morphodynamic models are applied to the study pond for simulations of both event-based scenarios and long-term flow events over a 32-year period (1984–2015), so further investigating the flow and sediment dynamics in the pond.

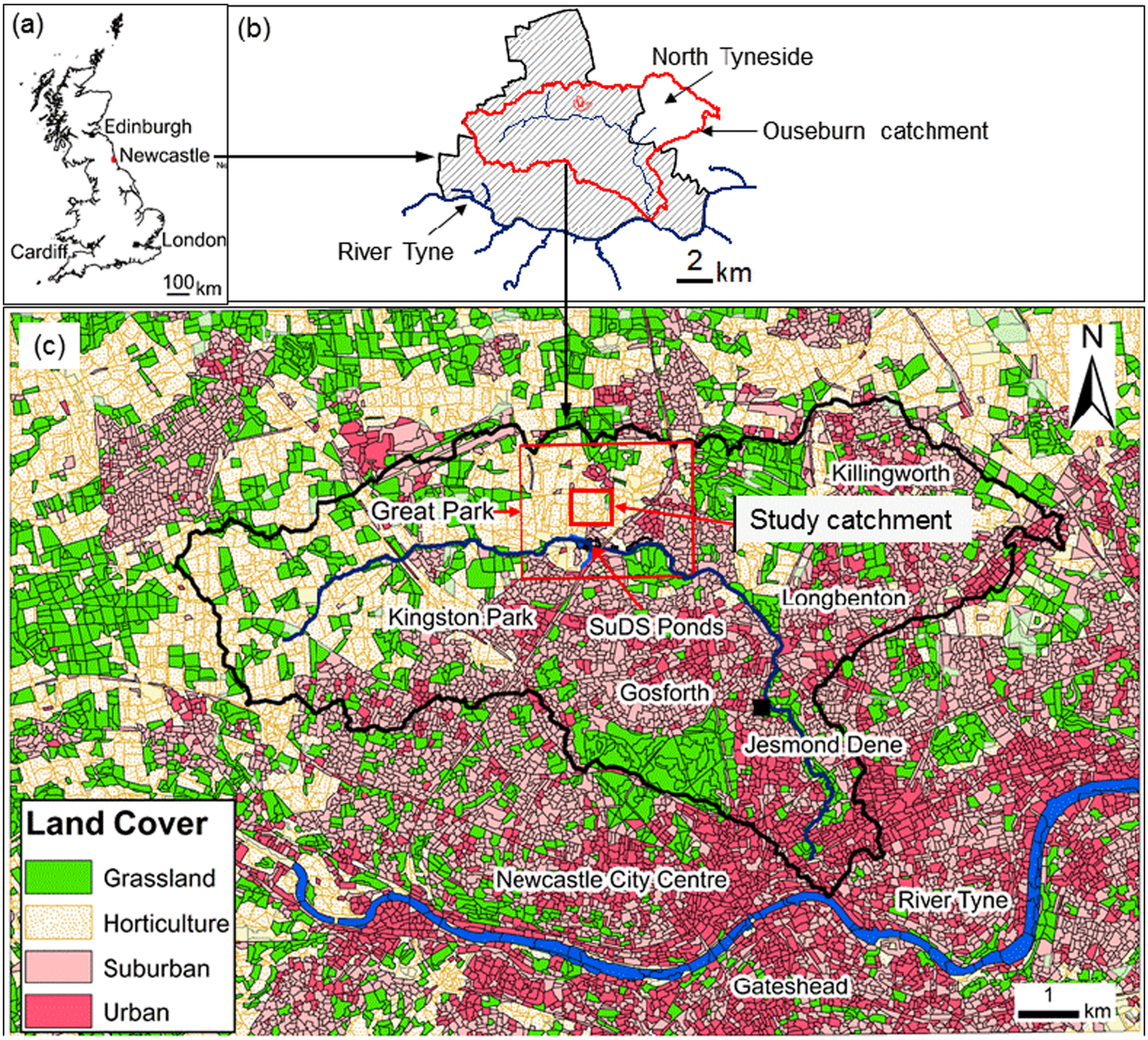


Fig. 1. Ouseburn catchment.

1.3. Research questions

The study investigates the following research key questions:

1. How does the stormwater pond influence flow and sediment dynamics during non-flood condition (5-year), designed drainage condition (30-year) and flood condition (100-year)?
2. What role does historical rainfall play in flow and sediment dynamics in the stormwater pond?
3. How does sedimentation evolve in the pond over time?
4. How does sedimentation affect the flood attenuation capacity of the pond over time?
5. How annual rainfall influences the annual sediment budget of the pond?

2. Study area

The Ouseburn is a 20 km long urban tributary of the River Tyne, located in North-East England, and serves as the study region (Fig. 1).

The Ouseburn catchment (60.5 km^2) covers large areas of urban Newcastle and North Tyneside (Fig. 1b). The upper reaches of the Ouseburn catchment are predominately agriculture and cultivated grasslands. The mid and lower catchment occupies a large residential area with a population of 166,000 people in 70,000 households (Newcastle City Council, 2013) in the Newcastle-upon-Tyne region (Fig. 1c). The catchment geology comprises the Carboniferous Middle Coal Measures (British Geological Survey, 2016). The large proportion of highly developed areas increases the risk of rapid surface water and fluvial flooding. The Ouseburn has a history of flooding (e.g. most recent flooding in June and August 2012), which had very serious environmental and socio-economic impacts (Newcastle City Council, 2011, 2013, 2016). The standard average annual rainfall (SAAR) of the Ouseburn catchment is 666 mm (calculated between 1985 and 2014, with a minimum 314 mm in 1989 and a maximum of 1,053 mm in 2012) (FEH, 2015). The SAAR is relatively lower than other regions at a similar latitude in the world due to warming influence of Gulf stream through the North Atlantic drift. Furthermore, Newcastle is in the rain shadow of the northern Pennines which protects the city from heavy rainstorms. The Ouseburn catchment currently fails to comply with the EU Water Framework Directive (WFD) water quality targets for Good status, due to high faecal, ammonia and phosphate levels which have an adverse impact on the river's ecological health (Turnbull and Bevan, 1995; Baker et al., 2003; Newcastle City Council, 2016). Ouseburn river is considered as a typical complex and challenging UK urban river as a result of a variety of pollution sources and their dispersed nature, which are difficult to quantify and address.

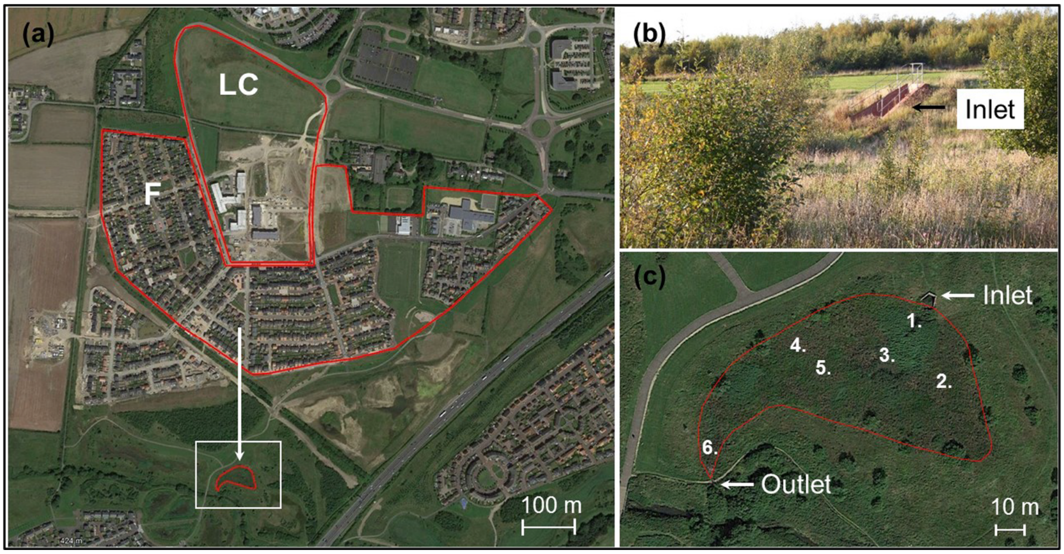


Fig. 2. Newcastle Great Park and study pond.

The study area focused on the midsection of the Ouseburn catchment and Newcastle Great Park development which is the largest housing and commercial development in the North-East England encompassing 2,500 residential dwellings, commercial premises and community facilities when complete. The development site covers 4.85 km^2 (485 ha), sub-divided into a number of development cells.

In order to comply with the Environment Agency controls on discharge rates to the watercourse based on greenfield equivalent flows, a number of stormwater retention ponds are integrated with the development site. This study focuses on the impact of a specific pond (Fig. 2a) on long-term flow characteristics and suspended sediment dynamics.

The pond serves a catchment area of 0.4 km^2 represented by development cells F and LC immediately north of it (Fig. 2a) with a total impermeable area of 0.2 km^2. Cell LC consists of a school, a community centre and a health centre, and cell F is primarily residential (850 properties) and transportation land uses. Urban runoff from cells F and LC is discharged into the pond through sewer network (Fig. 2a). The pond can be bounded within a rectangular shape (67 m × 77 m, length × width), and it has a surface area of about 2400 m^2 and an average depth of 2.2 m (volume of 6,533 m^3). A 3.5 m long concrete apron is placed in front of the inlet to the pond to ensure the flow entering the pond is evenly distributed so that stagnant zones do not develop over time in the pond. The pond is densely covered with emergent and submerged aquatic vegetation (Fig. 2b). The weir at the outfall regulates the rate of discharge to the Ouseburn River for a range of water levels, thereby filling the pond during storm events.

3. Data and methodology

The study adopts Revitalised Flood Hydrograph (ReFH) rainfall-runoff model to translate historical rainfall series into flow series which is then fed into the two-dimensional Layer-based Hydro-Morphodynamic Model (LHMM) to understand long-term suspended sedimentological effects on stormwater pond geometry. The methodology adopted in the integrated hydrological and hydro-morphodynamic model setup and simulation is shown in Fig. 3.

The Ouseburn catchment's topography, rainfall, land-use and sediment data sets were systematically collated from data provided by the Environment Agency and the UK Ordnance Survey along with design drawings of the Newcastle Great Park and field investigations. The Digital Terrain Model (DTM) data sets at 1 m resolution were obtained from the Environment Agency and represent the topography of the Ouseburn catchment. To assess relative impact of the pond on flood event hydrological and morphological responses, two DTM data sets were incorporated in LHMM model setup.

The current DTM represents the existing topography ('with pond') condition (Fig. 4c, d) and the DTM from the year 2000 represents the predevelopment stage of the terrain ('without pond') (Fig. 4a, b) scenario in the hydro-morphodynamic model. In addition, a river survey data along the Ouseburn was obtained from the Environment Agency ISIS (now known as Flood Modeller Pro) river model. The survey data were used to modify the channel and bank elevations in the DTM. Further, design drawings of the retention ponds were obtained from Newcastle City Council which were used to incorporate finer details such as design levels of the inlet, outfall weir control elevation and existing links with other ponds in the LHMM model. As part of the study, a number of field visits have been made to assess existing geographic and environmental features of the stormwater pond and Newcastle Great Park development. The field surveys allowed verification of the available data sets and maximised their usage by integrating them in the model development.

4. Numerical modelling

4.1. ReFH – hydrological model setup

The ReFH model is a physically-based conceptual rainfall-runoff model (Kjeldsen et al., 2005; Kjeldsen, 2007). The ReFH model includes three submodels: a loss model, routing model and a base flow model. The ReFH model allows a direct and transparent quantification of flood-generating mechanisms, and the concept of seasonal variation in soil moisture content and design rainfall.

The ReFH rainfall-runoff model provides a basis for hydrological modelling which will generate an understanding of the erosion process in the stormwater pond. Based on field assessments, details of the Newcastle Great Park development master plan (Fig. 2) and Northumbrian Water drainage network drawings, the cells of the development contributing to the study pond are identified through flow schematisation. In the next part, the Newcastle Great Park OS Mastermap data sets were used to classify impermeable areas that drain to the pond using systematic GIS analysis of land use feature classes. The soil data and catchment characteristics of the study region were obtained from the British Geological Survey and Flood Estimation Handbook data respectively. The catchment land use and geology data sets allow establishment of the initial infiltration loss and runoff characteristics in the ReFH hydrological model.

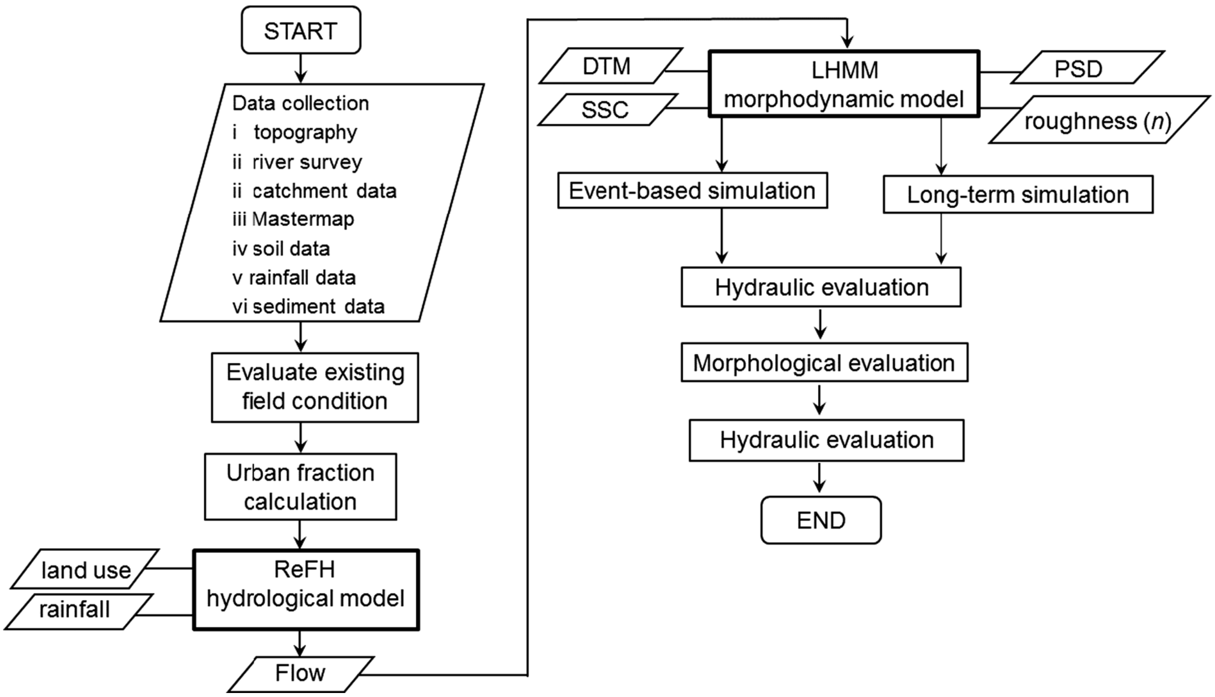


Fig. 3. Flow chart for integrated hydrological and hydro-morphodynamic modelling procedure.

In the first part of the study, the ReFH rainfall-runoff model is calibrated with the field data sets. The continuous flow measurements from 2015 January to May at the pond's inlet were taken as part of this study (Fig. 5).

A major proportion of the measured flows are low except for three larger flow events that occurred between 02/May/15 and 11/May/2015. Since the low flows are mainly driven by the base flow, the rainfall driven larger flow events are used in the ReFH hydrological model calibration (Fig. 5). The drainage length parameter (DPLBAR) which implicitly represents the drainage network of the catchment in the model is iteratively adjusted to match the measured flow at the inlet as part of the calibration process. Fig. 5 shows that the ReFH model

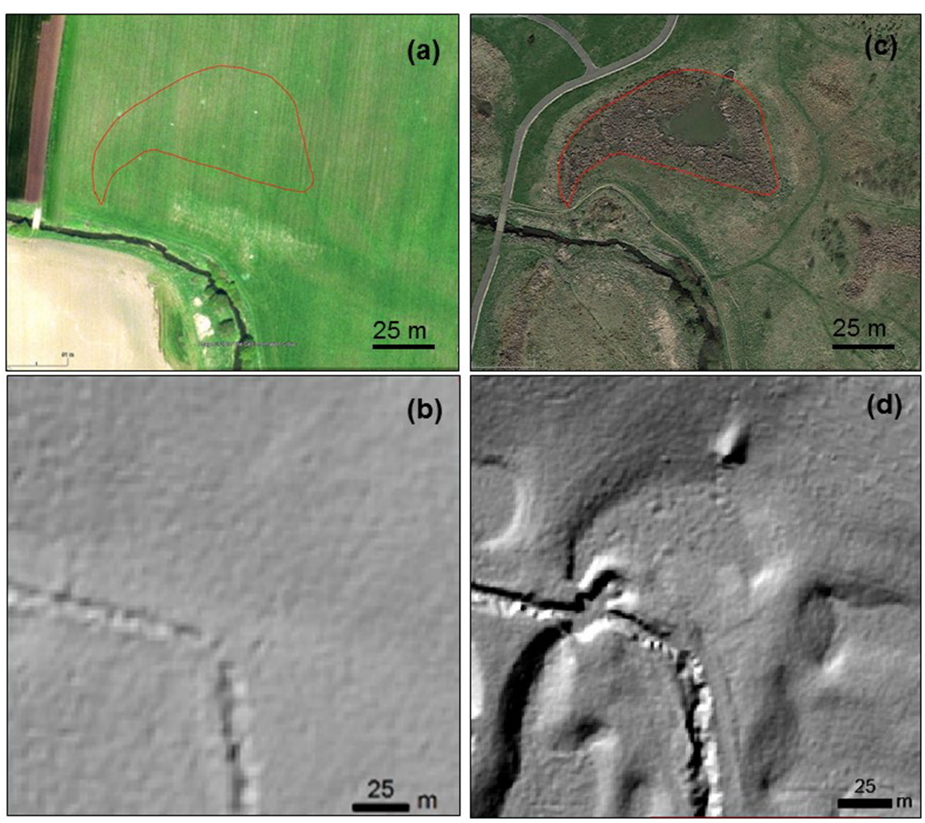


Fig. 4. Predevelopment aerial view (a), topography (b) and current aerial view (c), topography (d).

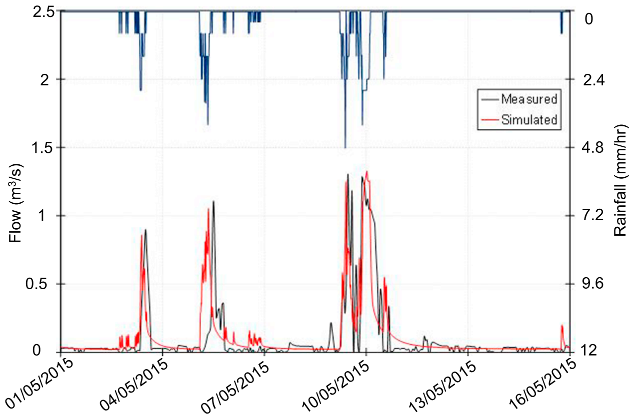


Fig. 5. Measured and simulated flow at the pond inlet.

produces inflow hydrographs that compare favourably with measured hydrographs. However, it should be noted that the limitations of the ReFH approach are the same as those in most conceptual rainfall-runoff models. The ReFH model slightly underestimates the magnitude and timing of the flood peak for most of the simulated hydrograph, except the last one. This difference is partly due to pipe networks and ground water levels which are not explicitly included in the ReFH hydrological model and calibration process. Since the primary aim of the study is to extend runoff series to evaluate long-term sediment dynamics, this level of variation in the flow input is deemed to be adequate. In the next stage, the ReFH model is used to transform three 1-hr duration hypothetical rainfall events into flood hydrographs such as non-flood (5-year), sewer design (30-year) and river flood (100-year) conditions (Fig. 7), for event-based simulations.

Historical rainfall data sets from the Jesmond Dene gauging station (EA #19356) were obtained from the Environment Agency. The rainfall data sets were carefully analysed for anomalies and infilled for missing data using the neighboring rain gauge data sets. The rainfall events which last more than 1 h or rainfall depth which exceeds 1 mm in a shorter time interval are included in the long-term sediment simulation (Fig. 7a). In total 3896 rainfall events were identified over the 32-year period (1984–2015) from the 15 min interval historical rainfall records. Their use allows the incorporation of a wide range of rainfall volumes, durations and intensity combinations to be incorporated in the hydrological simulations to represent the real-life scenario (Fig. 6).

The rainfall events show considerable variation in rainfall duration (0.25 – 42.75 h) and amount (0.6 – 93.8 mm) (Fig. 6(a)). The major proportion of historical storm events in the study period (1984 – 2015) are small events (< 5-year). However, they can have considerable influence on the urban runoff quality, as the cumulative effect of a large number of small storms is critical in stormwater quality management as opposed a few extreme events in flood management (Hall et al., 1993; Urbonas and Stahre, 1993). Furthermore, the more frequent flow events (< 5-year) typically cause sediment hotspots whilst larger events (> 25-year) re-suspend the accumulated sediments in stormwater ponds and on floodplains (Ahilan et al., 2016; Pender et al., 2016). Thus, it is necessary to incorporate a range of potential flood events in morphodynamic simulations in order to fully capture the dynamics of sediment deposition, erosion and transportation processes. There is also considerable variation in the intensity of the identified rainfall events over the study period Fig. 6(b). Amongst the 3896 studied historical storm events, 75% of the rainfall intensities are below 1.6 mm/h. The long-duration less-intense frontal rainfall events mostly occur in winter months which can cause fluvial flooding. Also, several short-duration high intensity convective rainfall events occur in summer months, often leading to pluvial flooding in the urban catchment, such as the 20.32 mm/h event on 28/June/2012, later dubbed the 'Toon Monsoon' (Newcastle City Council, 2013) and the 20.8 mm/h event (02/Aug/

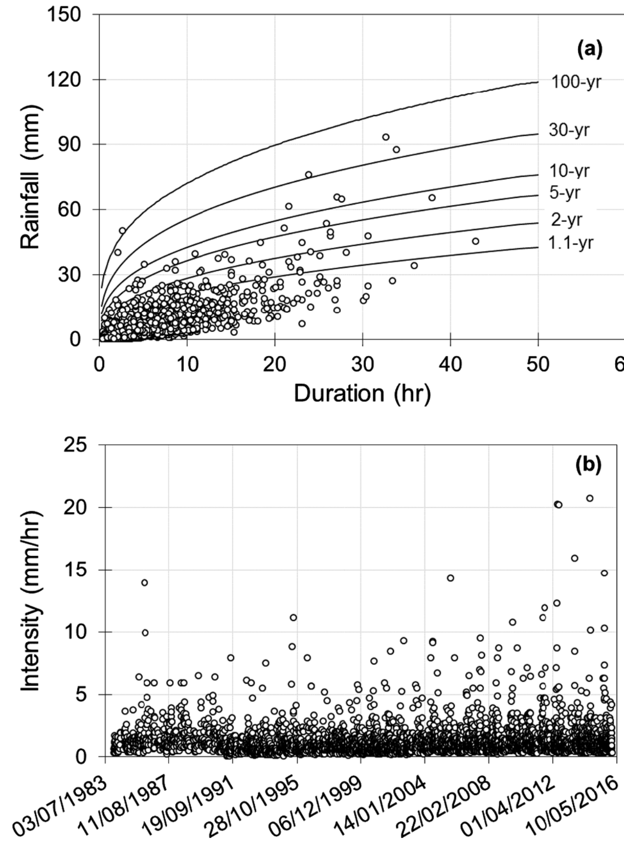


Fig. 6. Observed rainfall depth-duration-intensity relationship.

2014) which caused flooding in Newcastle city (Newcastle City Council, 2015, 2016). The combination of convective and frontal storm events in the data sets enables investigation of the influence of the pond on flow and sediment dynamics in detail over long periods of time.

In the next part, the identified historical rainfall events are continuously routed through the ReFH hydrological model to generate corresponding flow events. The flood peak of the simulated flow events varies from 0.5 m^3/s to 3.6 m^3/s.

4.2. LHMM – hydro-morphodynamic model setup

The LHMM is a two-dimensional (2D) non-equilibrium sediment transport model (Guan et al., 2014, 2015a,b). The model encompasses three modules: hydrodynamic, sediment transport and bed deformation models. The hydrodynamic model incorporates the mass and momentum exchange between flow and non-cohesive sediment and updates the hydraulic and sediment quantities per grid cell, and per time step. The sediment transport model controls the sediment mass conservation whilst the bed deformation model updates the bed elevation under erosion and deposition. The model solves the fully coupled shallow water equations (SWEs) together with a sediment transport model by using a robust Godunov-type finite volume method based on rectangular grids. The model can be used to simulate flow propagation, transport of both bedload and suspended load, as well as the resultant morphological change. The LHMM has been successfully applied in modelling sediment transport and morphological changes during flooding in a number of laboratory and field-based case studies (e.g. Ahilan et al., 2016; Guan et al., 2016; Guan et al., 2018). The hydro-morphodynamic simulations allow detailed inspection of flow velocities, water levels and suspended sediment dynamics in the retention pond for a range of flood conditions.

The field evidence in the Newcastle Great Park development shows that suspended load is dominant in the stormwater pond. This study therefore adopts LHMM with a suspended load model which is governed by an advection-diffusion equation in the model. The DTM and river survey data is used to represent the topography of the pond and the outlet (Fig. 4b, d). The pond is densely covered, primarily around the periphery by the native vegetation (Fig. 2b), the Manning roughness ($n = 0.04$) is used to represent the surface roughness in the hydromorphodynamic model. Sediment surveys were carried out using sediment traps and the particle size distribution (PSD) of samples was determined by laser diffraction using a Malvern Mastersizer S (long bench). The PSDs were obtained from the sampling at the pond inlet: D10 = 5.00 μm (fine silt), D50 = 12 μm (fine silt), D90 = 50 μm (silt), and were equally distributed as an input in the upstream boundary. The LHMM model requires a relationship between the stream flow, turbidity and suspended sediment concentration at the upstream boundary.

In the absence of long-term sediment data measurements in the Ouseburn catchment, the regression relationships between flow, turbidity and suspended sediment concentration were transferred from the analogue catchment (Johnson Creek, Portland), which exhibited similar land use patterns to the Ouseburn catchment (Ahilan et al., 2016). The following regression relationships between stream flow (Q), turbidity (T) and suspended sediment concentration (SSC) were established based on the continuous stream flow, turbidity and suspended sediment concentration measurements over four water years (2007–2010) (Stonewall and Bragg, 2012):

$$\log_{10}T = 0.455\log_{10}Q + 0.243 \quad (1)$$

$$\log_{10}SSC = 1.024\log_{10}T + 0.143\log_{10}Q - 0.64 \quad (2)$$

where Q in m^3/s, T in Formazin Nephelometric Units (FNU) and SSC in mg/l. The Eqs. (1) and (2) were used to establish the boundary condition at the pond inlet. The model prediction is initially validated with measured sediment data. Sediment samples were taken in the pond at monthly intervals over six months between 30/Jan/2015 and 23/June/2015. Samples were collected using standard surface measures (British Standards Institution (BSI)) and sediment traps and core samples from six locations at the bed of the pond, one at the pond outlet and three within the receiving water body (Fig. 2c).

The samples represent the total SSC and total bed deposition at each of the six locations. In the model validation, flow events between 23/April/2015 to 26/May/2015 were considered and results compared with observed sediment data of this period. The other five months are largely dominated by low flow and were excluded from the simulation (Fig. 5). The simulated and observed sedimentation depth at each of the six locations is shown in Table 1.

The measured and simulated sedimentation depths compare reasonably well for most of the locations in the pond. The discrepancies are mainly because of the influence of vegetation on the sediment dynamics and approximation in the input sediment data sets. Since the primary objective of this study is to understand long-term sediment dynamics in the pond, this level of variation in the model prediction is deemed to be acceptable.

Table 1
Simulated and observed sedimentation depth in the pond between 23/04/2015 to 26/05/2015.

Sampling location	Simulated depth (mm)	Measured depth (mm)
1	10.6	8.7
2	7.1	7.7
3	7.8	7.6
4	4.0	7.4
5	3.2	2.9
6	0.1	0.3

5. Results and discussions

5.1. Hydrodynamics of the pond

Fig. 7b–d illustrates the hydrodynamic performance of the pond for the three hypothetical flow events: non-flood condition (5-year), sewer design condition (30-year) and flood condition (100-year).

Fig. 7b–d shows that all three flow events experience attenuation and delay in flood peak at the pond outlet. However, the effects are more pronounced for more frequent flow event (5-year) than extreme event (100-year). The pond provides flood storage of 4.86×10^3 m^3 and 6.25×10^3 m^3 for 5 and 100-year flood events which reduces the flood peak by 85% and 30% respectively. The pond was originally designed to provide green field runoff for the 30-year flood event to the Ouseburn river, which is equivalent to 0.73 m^3/s. However, simulation results show that attenuated flow for 30-year event is 1.7 m^3/s, which is much higher than design flow (0.73 m^3/s). This inefficiency in pond flood attenuation capacity is partly due to pond design, pond location within a catchment and the land use within the contributing catchment. The pond provides detention times of 0.6 h and 0.2 h for 5-year and 100-year events respectively which is a measure of how much time water is retained in the stormwater pond before being discharged into the river. The detention time is estimated by the time lag between the centroid of the inflow and outflow hydrographs. The detention time is one of the critical parameters which influences the sedimentation and associated water quality benefits from the pond. Longer detention times allow sediment to settle in the pond and yield higher water quality benefits. To investigate impact of the stormwater pond on historical flow events similar analysis is carried out for the largest 39 historical events from the 3896 events.

The flood peak and volume of the identified historical events vary from 0.3 m^3/s to 3.8 m^3/s and 1,950 m^3 to 40,632 m^3 respectively. Fig. 8 shows the maximum inflow and outflow of the 39 historical events at the pond inlet and outlet respectively. It indicates that, more frequent small (< 5-year) and medium (< 30-year) flow events experience relatively higher flood peak attenuation, e.g. up to 77% (June 6, 1990), as a significant proportion of the small and medium flow contributes to filling up the available storage in the stormwater pond. Analysis has also shown that, stormwater pond provides minimum volume of 967 m^3 (15% of pond volume) for these 39 historical events. In the higher flow events, flood attenuation on inflow hydrographs are diminished as most of the detention storage of the pond is filled with a relatively smaller proportion of flow. The largest historical event occurred on September 5, 2012 where 15% reduction in the flood peak magnitude at the pond outlet was experienced.

5.1.1. Variation in detention efficiency and practical implications

Further analysis is carried out to investigate the impact of the pond on detention efficiency (Eq. (3)) of three hypothetical and 39 historical flow events.

$$\text{Detention efficiency (\%)} = \frac{\text{Peak discharge reduction(\%)}}{\text{Area controlled by detention(\%)}} \quad (3)$$

where ‘peak discharge reduction (%)’ refers to attenuation in inflow peak with respect to its peak and ‘area controlled by detention (%)’ is the ratio between pond surface area and contributing drainage area respectively. Fig. 9(a) and (b) explore the influence of flow peak and flow volume on detention efficiency of the stormwater pond, whereas Fig. 9(c) and (d) investigate their impacts on the detention time.

The detention efficiency exponentially decreases with flood magnitude, Fig. 9(a) and (b). Small and medium flow events experience higher detention efficiency than larger flow events. However, detention efficiency varies considerably for small and medium flow events due to the stochastic nature of rainfall and its influence on runoff peak and volume combinations. This is partly due to a mixture of different flood

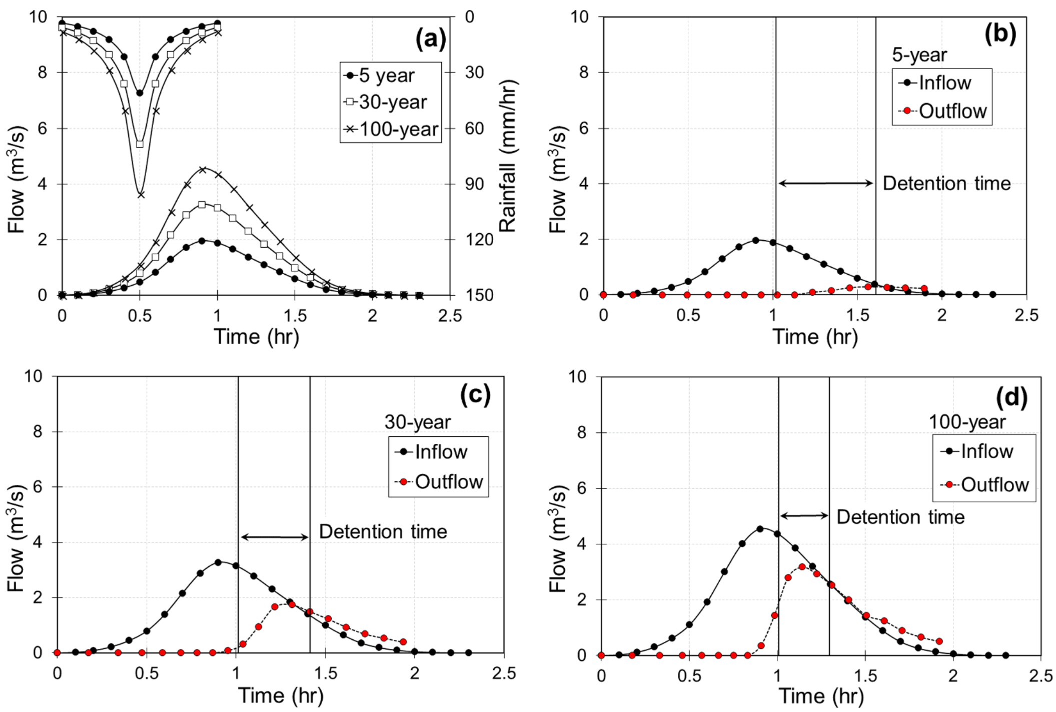


Fig. 7. Inflow and attenuated outflow hydrographs of the 5-year, 30-year and 100-year flow events.

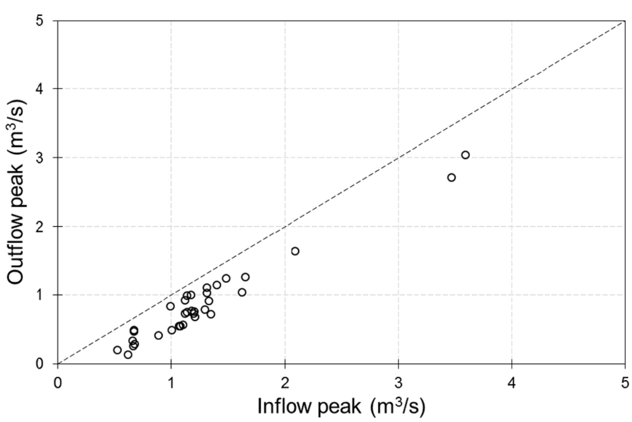


Fig. 8. Peak flows at the inlet and outlet of the pond.

types in the historical events which reduces the consistency of the regression relationships between the detention efficiency, flow peak and flood volume. In the UK, the long-duration less-intense frontal storm events occurring in winter months mostly generate flood events with higher volumes and lower peaks, while short-duration high intensity convective rainfall events in summer months result in runoff with lower volume and higher peak discharge.

Fig. 9(c) and (d) shows the variation in the detention time with flow peak and volume respectively for this pond. The detention time exponentially reduces with the flood magnitude (fitted with logarithmic distribution). The higher flow peak and volume events experience relatively shorter detention time compared with small and medium events. The flow volume and flow peak exhibit a relatively stronger relationship with detention efficiency and detention time respectively. Since detention efficiency and detention time are strongly associated with flood attenuation and sedimentation capacity of the stormwater pond, the design of detention basins where attenuation storage is involved should consider both the flood peak and volume of a number of potential flood events (Gaal et al., 2015). Given the inherent variability and presence of intrinsic relationships between detention efficiency, detention time and hydrograph properties (peak, volume and duration), the design hydrographs of the stormwater pond should be derived from the multivariate joint distribution rather than univariate functions. Using the joint probability distribution function of rainfall volume and duration together with catchment characteristics, a number of studies (Shiau, 2003; De Michele et al., 2005; Chen et al., 2010; Zegpi and Fernandez, 2010; Graler et al., 2013; Requena et al., 2013, Serinaldi and Kilsby, 2013; Gaal et al., 2015) have made an attempt to establish a deterministic relationship in hyetograph and hydrograph properties. This kind of approach should be integrated with pond design guidelines that will enable the calculation of the effect of inflow on storage, and the efficient design of the stormwater pond system.

5.2. Morphodynamics of the stormwater pond

The morphodynamic simulation results for three flow events for both the 'with' and 'without' pond scenarios are shown in (Fig. 10).

As expected, a considerable proportion of the sediment from the Newcastle Great Park is trapped in the pond under all three event-based scenarios (compare 'with' and the 'without' pond scenario). In the pond scenario, the flow depth increases and velocity decreases which causes settling of coarse sediment at the pond inlet. Density currents during larger flood events transport finer sediment particles closer to the outlet. The amount of sediment detained in the pond is 4.24 m^3 and 7.04 m^3 for 5-year and 100-year event respectively. The sediment hotspots in east and west sides of the pond are partly due to localised depression storage and presence of dense vegetation in these regions. To proactively increase retention time and facilitate sedimentation, the design of the pond could be improved by use of an inlet that dissipates inflow energy to reduce mixing, creatation of an island in front of inlet and installation of porous baffles with native vegetation which spreads the flow across the pond and lengthens the flow path east-west direction before reach to the pond outlet.

However, under the 'without' pond scenario, the volume of sediment deposited is 0.63 m^3 and 3.73 m^3 for 5-year and 100-year flood events. This indicates the significant benefit of the pond on sediment trapping. The proportion of the incoming sediment that is captured by the retention pond is called the trap efficiency (Heinemann, 1984).

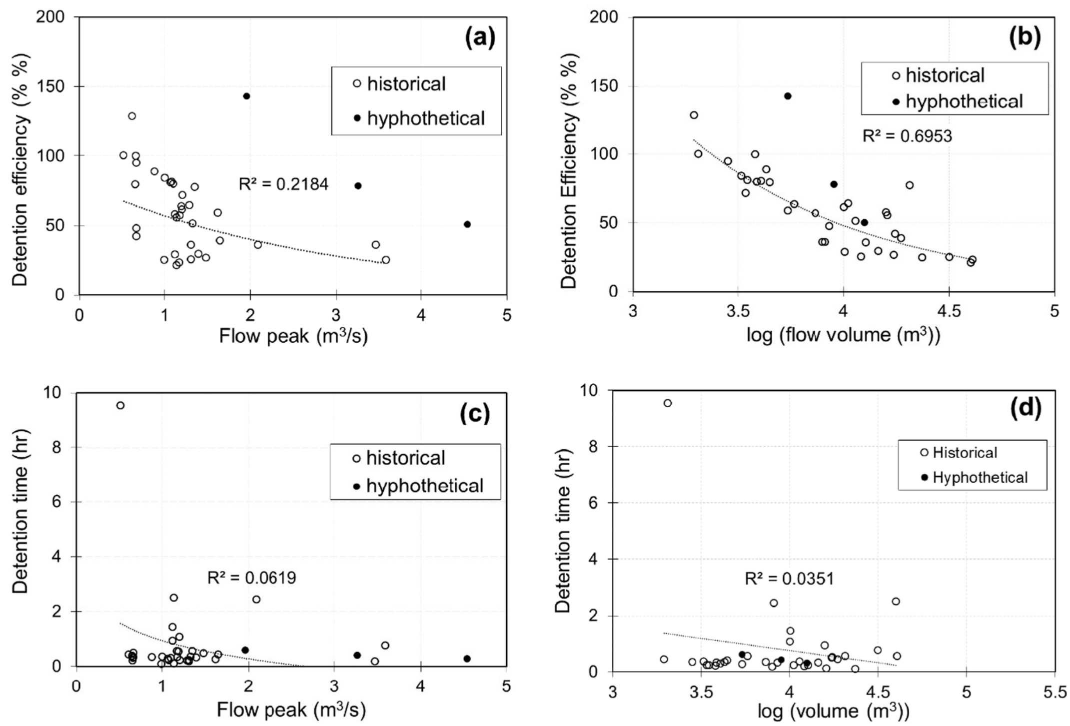


Fig. 9. Variation of the detention efficiency and detention time with flow peak and volume.

Table 2 compares the cumulative amount of sediment deposited into the pond with the total suspended sediment load (SSL) input at the outfall for different flood events for the 'with pond' scenario.

A significant proportion of the suspended sediment that comes from the development site is deposited in the retention pond for smaller (5-year) and medium (30-year) flow events. UK CIRIA and U.S. EPA reported removal of suspended solids by stormwater ponds as high as 67–81% (Woods Ballard et al., 2015) and 60–90% (U.S. EPA, 1983). In addition, Australian guidelines recommended the suspended sediment removal rate for the similar drainage area ratio (pond surface area/contributing catchment area) of around 80% (Healthy Waterways, 2006; Water by Design, 2010). In this case the removal rate is lower because of the short residence times and flow conditions are unfavourable for settling. The amount of sediment deposition increases with flood magnitude, but the percentage of the sediment trapped in the pond reduces when compared with total suspended sediment input for this pond over these simulated flood events. This is because the larger flood event creates high energy and a turbulent environment in the pond which increases the degree of mixing of the fine sediment material in suspension and transports this towards the outlet and subsequently, the river. The largest event also has the lowest detention time which limits the sediment settling in the pond.

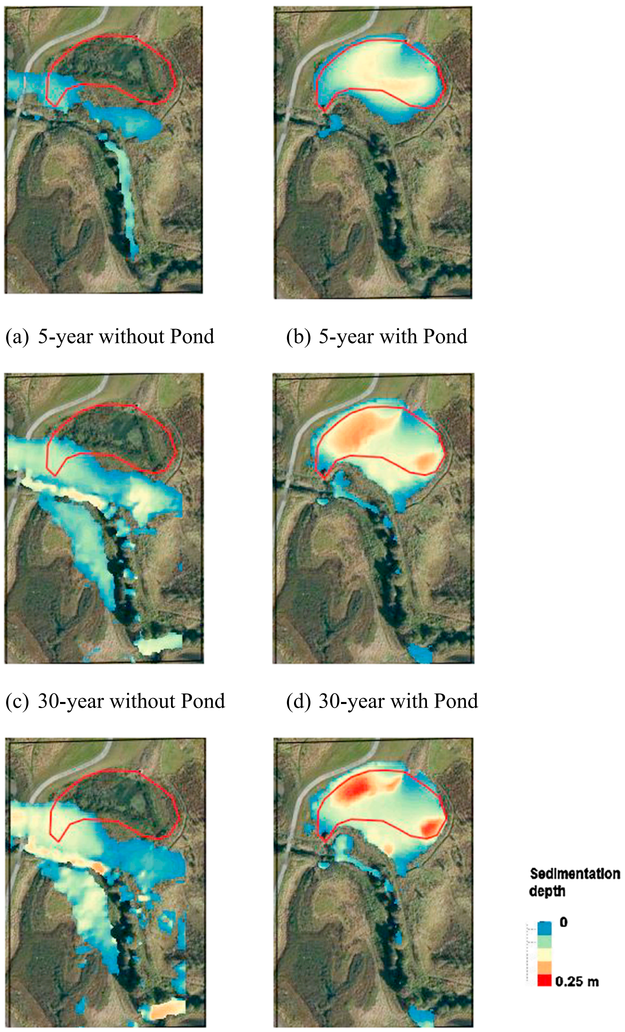
Fig. 11 shows the simulated temporal and spatial variation of the sediment deposition in the pond over the 32-year study period (1984–2015). It indicates that over time, sediment deposition non-linearly increases and moves towards the pond outlet direction. Most of the historical events with small and medium magnitude lead to temporary sediment detention and sediment aggradation in the pond. However, an extreme rainfall event in year 2012 – (year 29) Fig. 11, influences the overall sediment budget by flushing out the accumulated sediment as a shock load to the river system. On one hand, this process considerably reduces the sedimentation, enabling the pond volume and flood resilience capacity to re-establish. On the other hand, the shock load could lead to elevated concentrations of sediment and pollutants, resulting in dissolved oxygen depressions due to oxidation of contaminants. This can have adverse impact on water quality and biodiversity. However, it is difficult to establish the water quality standard for the stormwater systems due to the stochastic nature of rainfall events and the non-linear relationship between flow and sediment transport rate. The wastewater quality standards are thus unable to be adopted to a stormwater system due to randomness of rainfall events.

According to the model prediction at the end of the 32 years long-term simulation, 1,575 m^3 of sediment was deposited in the pond which is equivalent to 34% of the total sediment input. This resulted in a 24% loss in the pond's volume which is equivalent to a sedimentation depth of 0.65 m throughout the pond. The sediment aggradation could diminish the storage capacity while increasing the concentration of contaminants in the pond and eventually the groundwater beneath the pond. The temporal and spatial average rate of sediment accumulation of 2 cm/year is estimated as the average sedimentation depth divided by the pond cross sectional area and the period of accumulation (32 years). This low accumulation rate is supportive of temporary sediment detention within the pond and continuous conveyance of fine urban sediment pollution through the pond over cumulative events (indicated by fine sediment tracer studies undertaken within this pond illustrating < 5% long-term fine sediment detention).

5.3. Accumulation rates and their comparison with other studies

These findings on sediment dynamics in the pond are similar to previous few field-based studies (e.g. Yousef et al., 1994; Marsalek et al., 1997). For example, based on a field survey of the Kingston stormwater pond in Ontario (Canada). Marsalek et al. (1997) indicated sediment accumulation with an average rate of 2 cm/year. This was estimated by dividing the average length of sediment cores by the period of accumulation (10 years), and it resulted in a 13% loss in the permanent pond volume. Yousef et al. (1994) indicated a sediment accumulation rate varying from 1 cm/year to 4 cm/year based on the in-situ field measurements of sediment accumulation in nine highway wet ponds in central and south Florida, USA.

The analysis undertaken by Yousef et al. (1994) indicates that the sediment accumulation rate has a negative geometrical correlation with the drainage area ratio; there is a negative exponential trend in the sediment accumulation rate, with a sharp decline for drainage ratios



(a) 5-year without Pond (b) 5-year with Pond

(c) 30-year without Pond (d) 30-year with Pond

(e) 100-year without Pond (f) 100-year with Pond

Fig. 10. Sediment deposition for 5-year, 30-year, 100-year events for 'with' and 'without' pond scenarios.

Table 2
Sediment mass balance for different isolated flood events.

	5-year	30-year	100-year
Input (SSL m^3)	7.35	16.71	28.41
Deposited in the Pond (SSL m^3)	4.58	7.29	7.50
% SSL deposit	62.03	43.63	26.40

0–2% and shallow decline for ratios > 2%. In the Yousef et al. (1994) study ponds, a drainage area ratio of 1% and 12% yield corresponds to the maximum (4 cm/year) and minimum (1 cm/year) sediment accumulation rate. For our case study, the drainage area ratio is 0.6% and the simulated average sediment accumulation rate vary from 0.2 cm/year to 5 cm/year, lower bound of the simulation results is slightly smaller than field results presented in Yousef et al. (1994). A number of factors could have contributed to this difference. Firstly, the results presented in Yousef et al. (1994) are for ponds that have been operational for 7–28 years. The modelling undertaken for this pond has extended past this duration, to 32 years. Fine sediment tracing experiments have illustrated the temporary nature of urban sediment detention (Allen et al., 2015b, 2017) and thus it could be expected that the long-term sediment detention efficiency (accumulation rate relative to drainage ratio) would be smaller due to ongoing temporary detention and conveyance. Secondly, the differences in the two sets of results might have in part resulted from limitations in the input data for the hydro-morphodynamic model; these data are obtained from the analogue catchment and are used to establish the regression relationships between suspended sediment concentration, turbidity and flow.

Thirdly, inherent limitations in the hydro-morphodynamic model may hinder accurate representation of the effects of emergent and submerged aquatic vegetation on flow and sediment dynamics in the study pond (Fig. 2b). In the model, vegetation is represented by a higher roughness (Manning's n); however, this representation may not fully capture the interaction of the vegetation in flow processes and sedimentation patterns in the pond. The porous vegetation block exerts a drag resistance and alters the streamwise velocity which creates complex 3D flow patterns around them (Clarke, 2002). The vegetation markedly reduces flow velocity and turbulence across the pond and, subsequently increasing sediment deposition and trapping by localised advection and porosity. The vegetation also hinders scouring and re-suspension during heavy rainfall events. Fourthly, climatic variations between Newcastle-upon-Tyne, UK and Florida, U.S.A may result in variations in event occurrence and sediment wash off. The influence of a few extreme rainfall events in the study period in Newcastle-upon-Tyne could significantly influence the overall sediment accumulation rate and the comparison. Fifthly, associated turbulence resulting from wind shear stress can influence flow fields and sediment dynamics. Wind influence was not included in this modelling study.

Finally, the short circuiting of the flow to the eastern and western boundaries of the study pond to adjacent ponds (Fig. 2c) is expected to occur during extreme rainfall events. The case study pond and west side pond (Fig. 2c) are connected by an overflow pipe (~300 mm diameter) allowing high flows to be directly diverted into this western pond. This diversion and the adjacent connected pond(s) were not included in this modelling. The above factors could influence hydraulic performance and the annual sedimentation rate in the study pond at the Newcastle Great Park development.

5.4. Overall sediment budget and implications for maintenance schedule, water quality and residence time

Fig. 12 shows the cumulative sediment accumulation in the pond over the 32-year study period (1984–2015). Sediment continuously accumulates in the pond from 1984 to 2015 (except a small reduction in 2012) with an average sediment aggregation rate of 2 cm/year.

However, an extreme rainfall event occurred in June 2012 resulting in sediment erosion of 16 m^3. The 2012 flash flooding in Newcastle-upon-Tyne was caused by the 'Toon Monsoon'. On 28th June the highest rainfall with a total of 51 mm was recorded, of which 26 mm fell in 30 min, 32 mm in 1 h and 49 min (Fig. 6). The recorded rainfall within the 2-hour period is equivalent to the expected rainfall for the whole month of June in the summer of 2012, which is regarded as the wettest summer in 100 years (Newcastle City Council, 2013). The rainfall return period of the June 2012 events was estimated at up to 130-year for periods between 1 and 2 h. Fig. 12 also emphasises that loss of pond storage volume and benefit of sedimentation cannot be co-maximised. The pond could build up with 20 cm sedimentation over 10 years period with the sediment accumulation rate of 2 cm/year as happened between 1984 and 2015 which led to a 7.5% reduction in pond storage. Although the timing of the sediment dredging is dictated by the actual depth of silt build up, it would be necessary to carry out major maintenance on a regular 8–10-year cycle to maintain efficient pond operation. Sediment dredging should be organised and timed to minimise disturbance to freshwater habitats.

Fig. 13 shows the annual variation in sediment input and deposition in the pond, and the annual trap efficiency of the pond over the period. It indicates that sedimentation occurs in the pond during 31 years of the

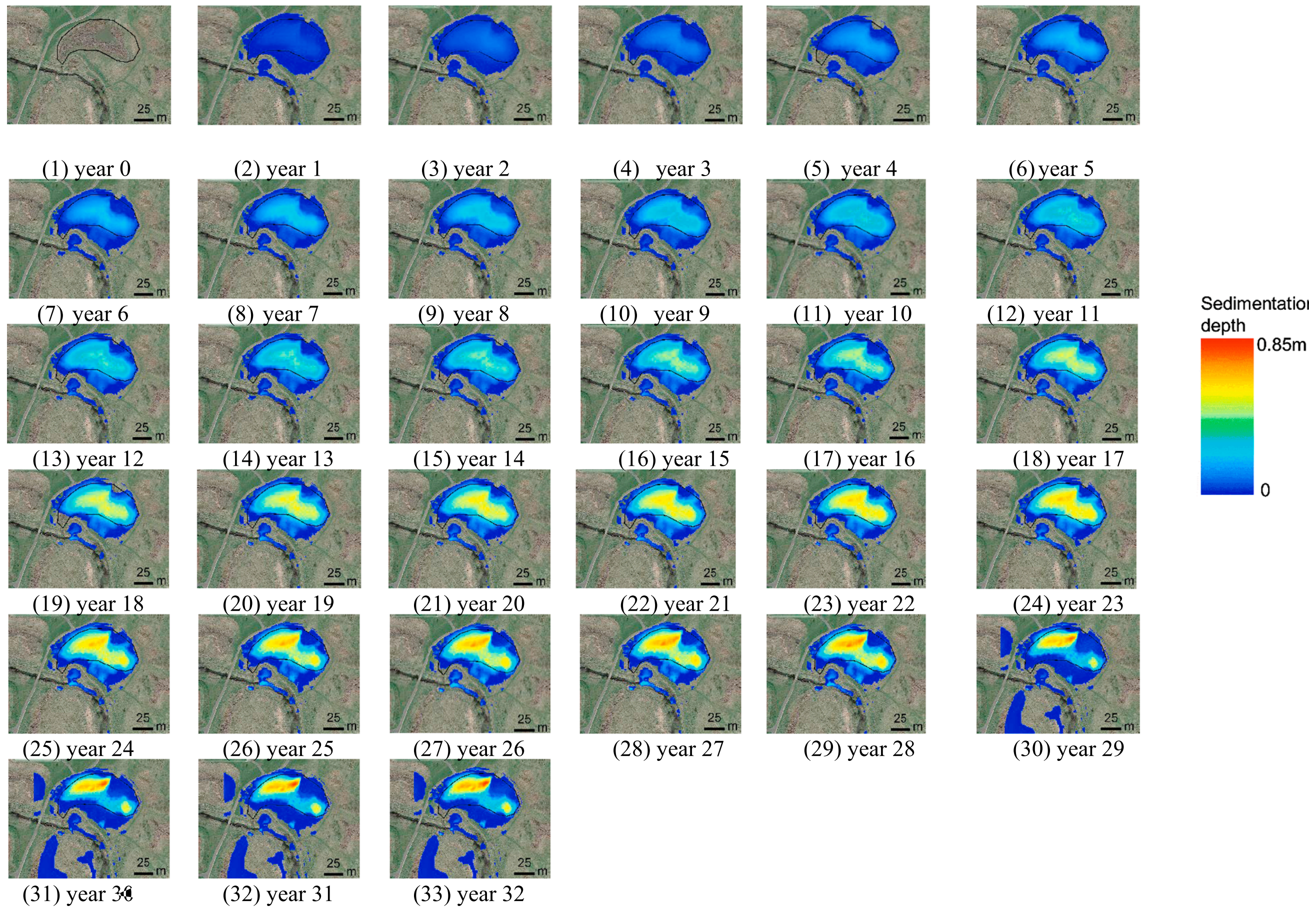


Fig. 11. Cumulative annual sediment deposition from 1984 to 2015.

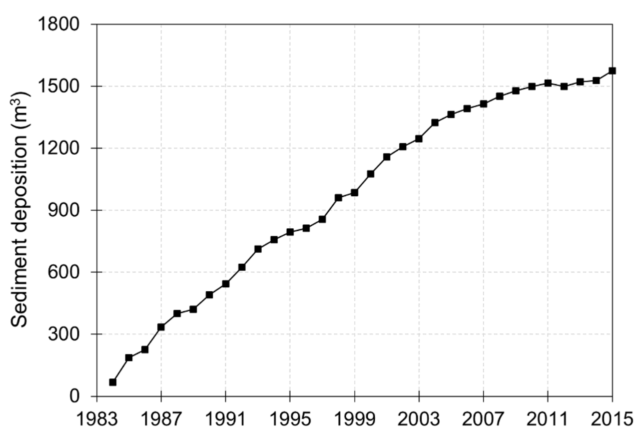


Fig. 12. Cumulative sediment accumulation in the pond.

32-year study period (1984–2015), resulting in a positive overall trap efficiency. During this 31-year period, trap efficiency varies from 69% in 1985 to 2% in 2014. However, in the year 2012, scouring occurred which resulted in a negative trap efficiency of 11%. In other words, the range in annual sediment trap efficiency over the 32-year study period is quite large (−11 to 69%) with the mean (SD) value of 34% (17%). The large variations in the trap efficiency due to the randomness in the rainfall emphasises the fact that it is difficult to comprehensively model or set water quality standards for stormwater ponds. Fig. 14 explores the influence of annual rainfall on annual suspended sediment input into the pond and sediment output from the pond over the 32-year study period.

Fig. 14(a) shows a positive correlation between annual rainfall and annual suspended sediment input into the pond as expected. This is because of inherent relationships between rainfall, flow and turbidity as described in Eqs. (1) and (2), which were used to develop inputs for the hydro-morphodynamic model. Since the annual runoff is a product of the annual rainfall, both the annual rainfall and the annual runoff depth have been used as a surrogate measure to estimate the annual sediment yield in a number of empirical models such as the Hydro-Physical model, Carson and Kirkby model (Carson and Kirkby, 1972), and Douglas model (Douglas, 1999). Fig. 14(b) shows a reasonably good correlation between the annual suspended sediment yields from the pond with annual rainfall. In a typical year, a major proportion of the rainfall events are small (< 5-year) or medium (< 30-year), which generally result in causing sedimentation within the pond. However, a few extreme rainfall events in a particular year could significantly increase rates of erosion, even though the change in annual rainfall is slight. The annual rainfall is not always sensitive enough to capture the influence of extreme events on sediment dynamics as it does not delineate the individual event intensity or duration or the time interval between successive events.

In order to investigate the long-term impact of sediment aggradation in the pond on flood attenuation capacity, hydrodynamic simulations are carried out after a simulated operational period of 5 years, 10 years, 20 years and 30 years for the pond, with a simulation of three isolated flood events after each operational duration. Table 3 shows the impact of sediment accumulation in the pond on flow dynamics for the 5-year, 30-year and 100-year flood events.

As expected flood storage reduction in the pond as a result of sediment aggradation increases the peak of the outflow hydrographs and reduces the relative attenuation and hydraulic residence time for all

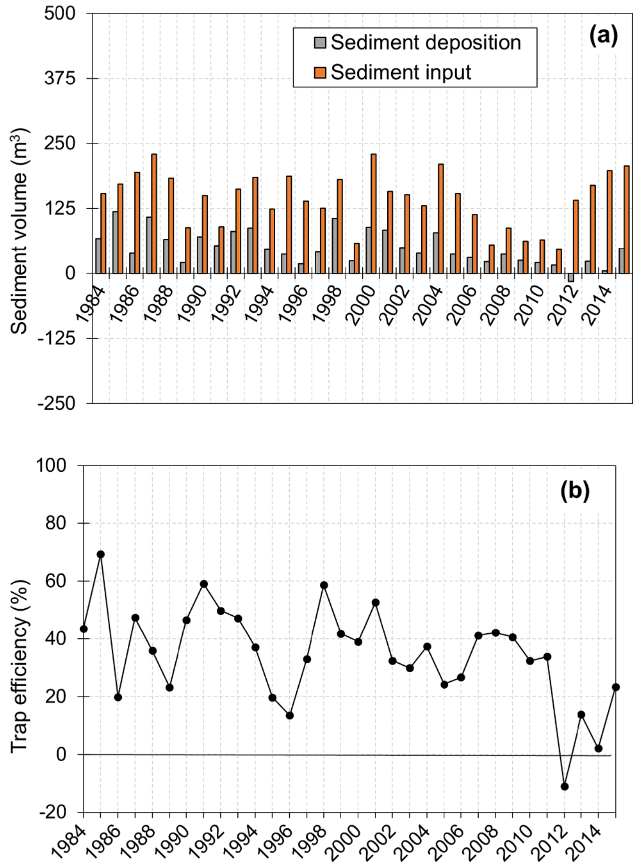


Fig. 13. Annual sedimentation and trap efficiency of the pond.

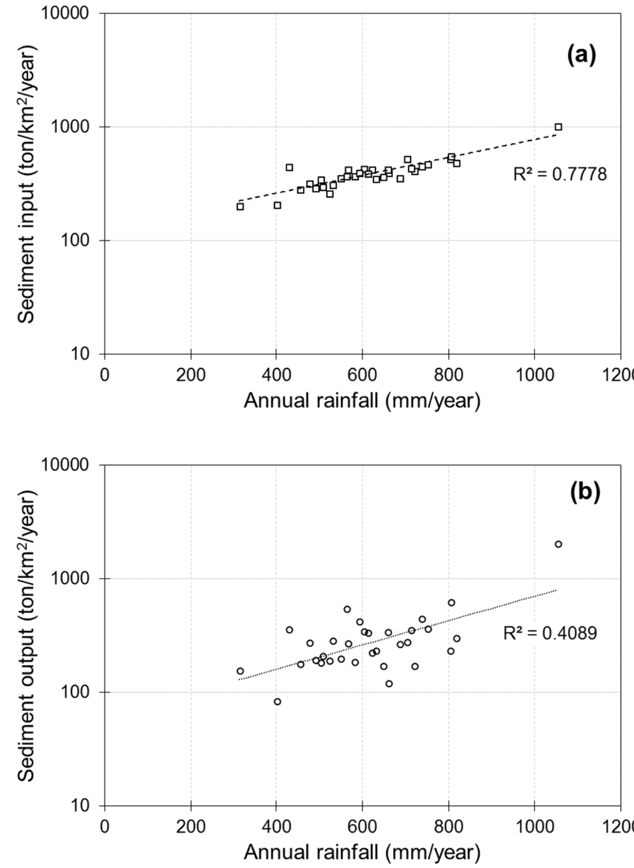


Fig. 14. Variation of annual sediment input and output from the pond with annual rainfall.

three events. As shown in Table 3, at the end of the 30-year simulation period, the 5-year and 100-year flood events experienced reductions in flood attenuation given as 8% (85%–77%) and 4% (30%–26%) respectively due to sediment aggradation. In other words, the effects are more pronounced for medium (30-year) and extreme (100-year) flood events than in more frequent small flood events (5-year). The reduction in flood attenuation capacity does not linearly increase over time as sediment dynamics primarily depend on inflow which considerably varies over time. For instance, the extreme flood events which occur in the intervening period between the 20 and 30 years of the simulation period flush out part of the accumulated sediment (major event in 2011–2012), offsetting the loss in flood storage and improving the flood peak attenuation capacity of the pond.

6. Conclusions

This paper examines long-term suspended sedimentological effects on stormwater pond, NE England by adopting integrated hydrological and a two-dimensional hydro-morphodynamic modelling approach. The main conclusions of this paper are as follows:

- Simulation results indicate that flow attenuation and sediment trapping in the stormwater pond are more pronounced for more frequent small (< 5-year) and medium (< 30-year) flow events. This is beneficial in regulating urban stormwater quality as a major proportion of the historical events encompass small and medium events.
- The annual sediment trap efficiency varies considerably (−11 to 69%) over the 32-year study period with the mean (SD) value of 34% (17%) which reflects that it is difficult to set water quality standards for stormwater pond due to randomness in the rainfall events.
- The spatially averaged sediment accumulation rate varies from 0.2 cm/year to 5 cm/year with the mean (SD) value of 2 (1.34) cm/year. Long-term sedimentation could have negative implications on flood attenuation capacity of the stormwater pond. The reduction in flood attenuation because of sediment aggradation is relatively more in medium (< 30-year) and large (< 100-year) flood events. Regular maintenance would be required after each 8–10 years period to maintain the efficient hydraulic performance of the pond and to reduce the risk of water quality deterioration due to remobilisation of pollutants accumulated in sediments.
- The annual rainfall exhibits a reasonably strong relationship with annual sediment input and output and could be used to estimate the annual sediment budget in the pond. However, the annual rainfall may not be sensitive enough to capture the influence of extreme rainfall events on sediment dynamics, suggesting caution when estimating the annual sediment budget when there are extreme rainfall events in the historical records.

The overall contribution of this paper has been to improve understanding of the flow and sediment dynamics of a stormwater pond, which ultimately may provide guidance to define maintenance needs, long-term design efficiencies and best practice for pond designers and operators.

Table 3
Impact of sedimentation on flood attenuation and hydraulic residence time.

	5-year Relative Attn (%)	HRT (h)	30-year Relative Attn (%)	HRT (h)	100-year Relative Attn (%)	HRT (h)
Pre-sedimentation	85.45	0.59	45.75	0.40	29.95	0.29
Post-sedimentation						
After 5 years	84.68	0.58	45.28	0.40	28.46	0.28
After 10 years	81.41	0.58	42.26	0.40	28.20	0.28
After 20 years	75.15	0.51	36.64	0.34	25.59	0.25
After 30 years	77.47	0.54	38.11	0.36	26.35	0.26

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Appendix A. Supplementary data

Supplementary data to this article can be found online at University of Nottingham data repository https://doi.org/10.17639/nott.6173.

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